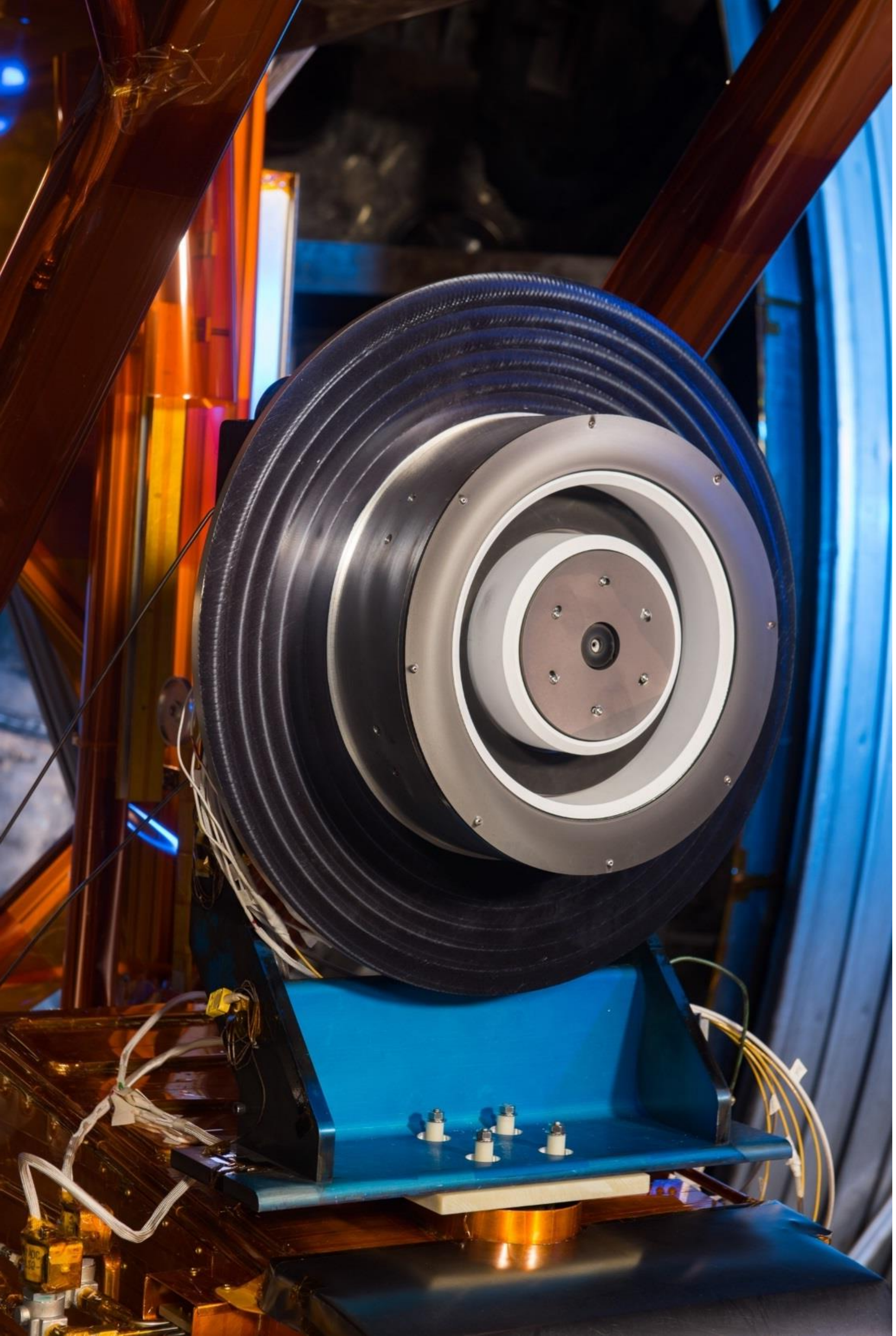

Uncertainty in Electric Propulsion Erosion Measurements

J. Mackey, J. Frieman, and D. Ahern

NASA Glenn Research Center, Cleveland, Ohio 44135

J. Gilland

Vantage Partners LLC, Brook Park, Ohio 44142

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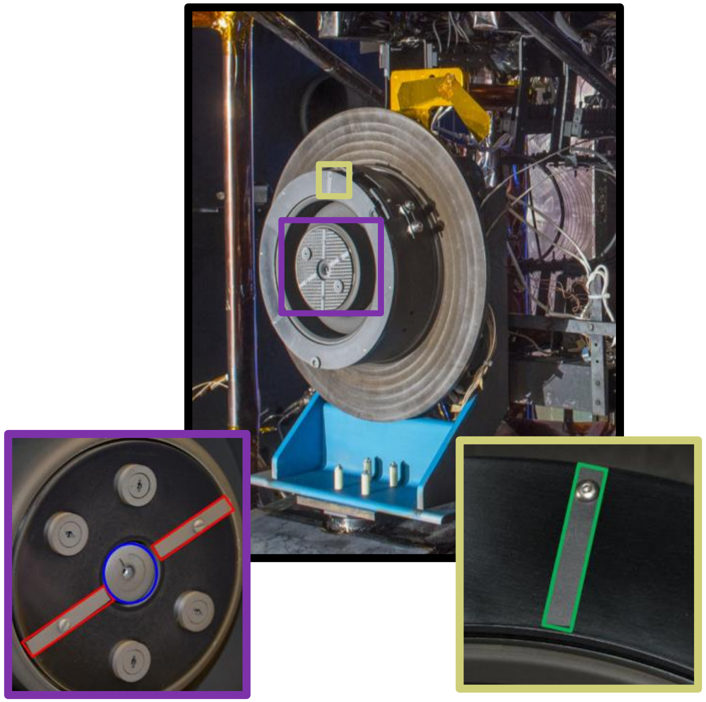
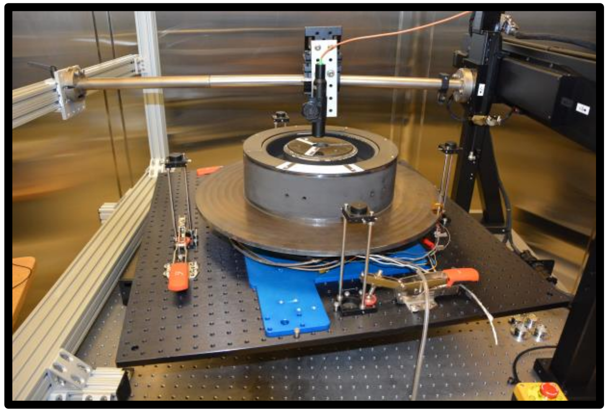
Introduction

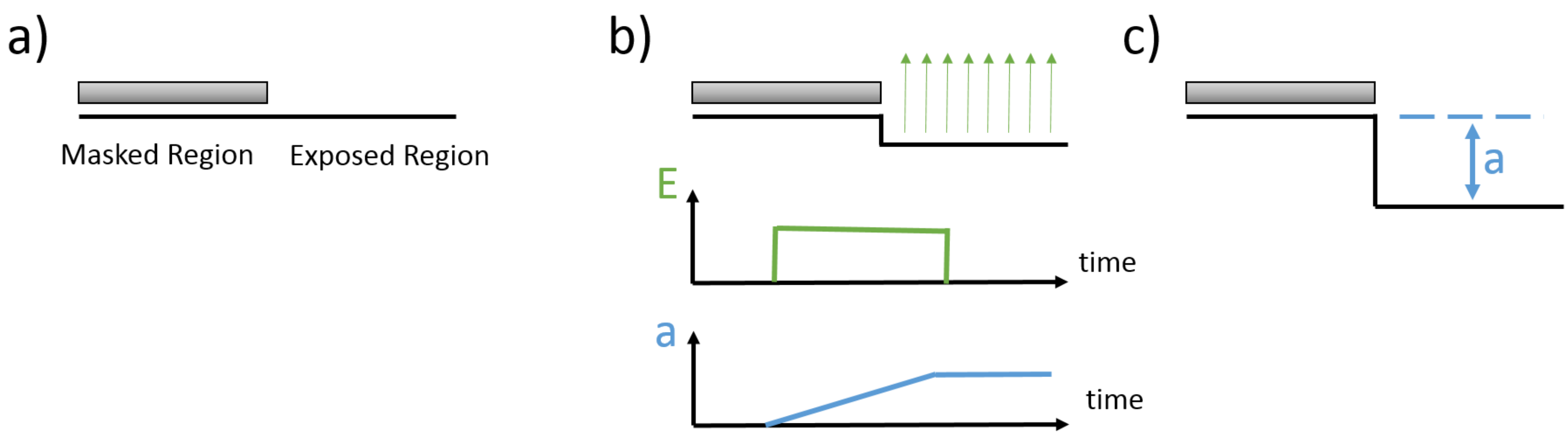
- Erosion measurement is critical to the characterization of electric propulsion (EP) systems.
  - Quantify: absolute erosion rate, trends with operation, trends with location on EP system.
  - Needed to understand and predict system lifetime.
  - Challenging because of low erosion rates.
  - Sources of potential error must be well understood for reliable data.
- Technology Demonstration Unit (TDU-3) thruster operated at NASA GRC in VF-5 and VF-6.
- Non-contact confocal profilometer scanning masked graphite components.





Model of an ideal masked erosion

Before | During | After

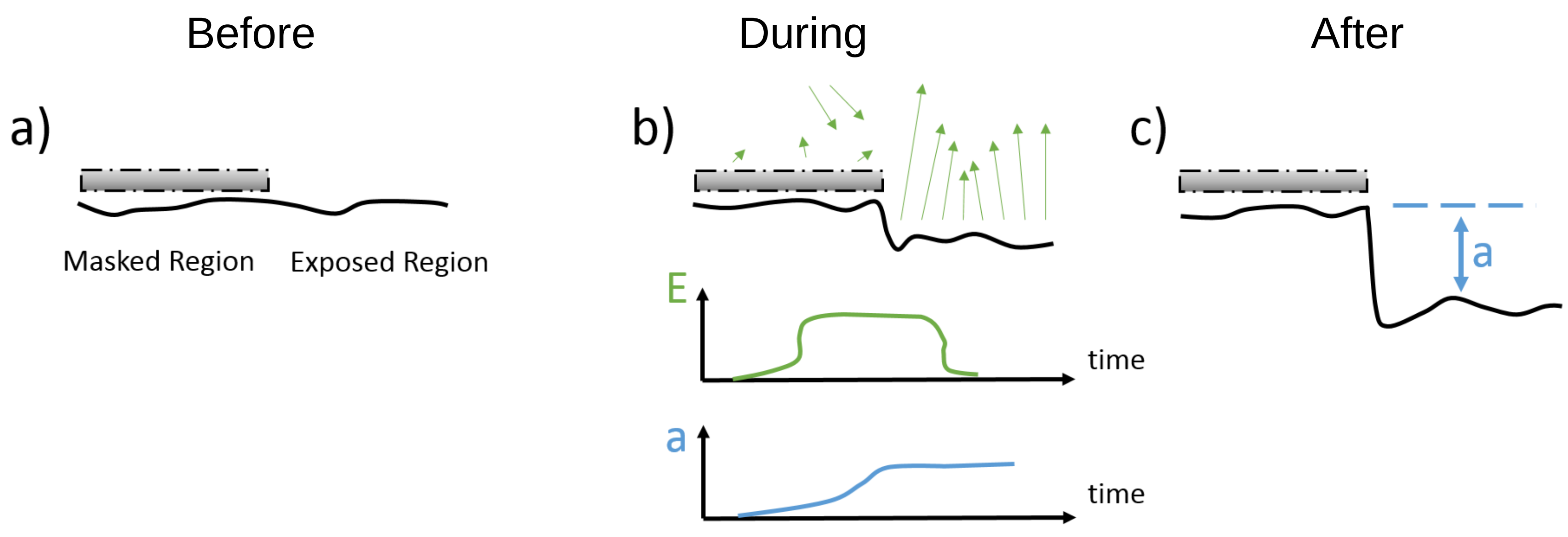


- Macroscopically flat
- Microstructurally smooth
- Locally homogeneous
- Mask does not interact
- Mask perfectly protects

- Steady state
- Spatially uniform
- Directionally invariant
- No back sputter

- Uniform step

Model of an ideal masked erosion



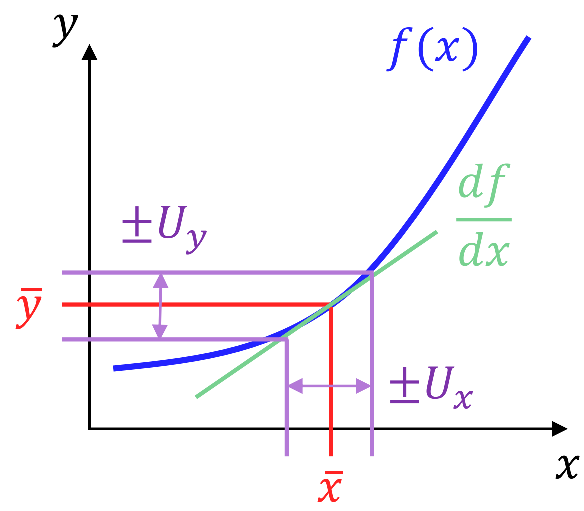
- Macroscopically rough
- Microstructurally rough
- Locally inhomogeneous
- Mask may interact

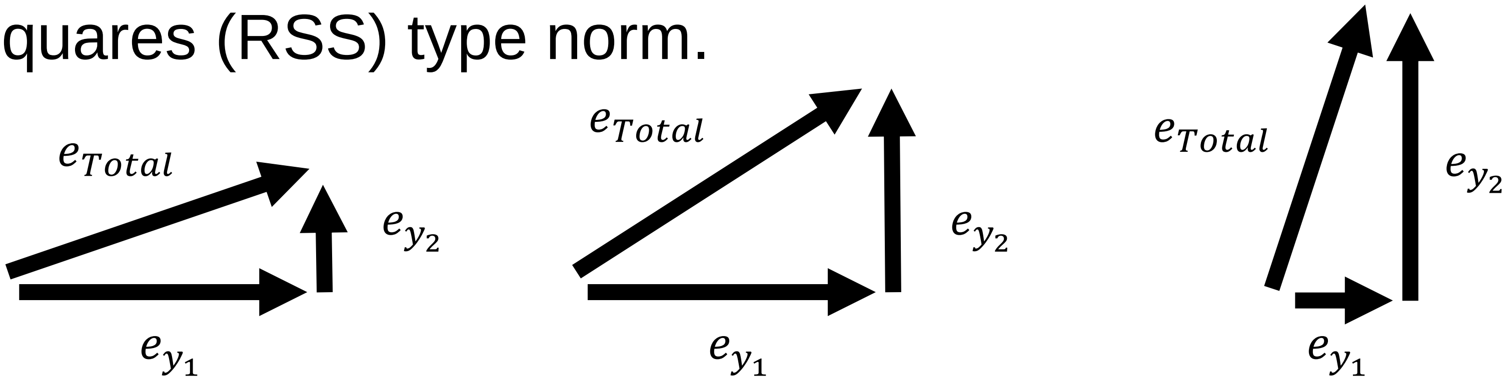
- Transient
- Spatially varying
- Directionally varying
- Facility back sputter
- Mask back sputter

- Non-uniform step

Methodology

- Classic approach of Figliola and Beasley, Abernethy et al., or Moffat.
  - Design-stage, single-measurement
- Propagate error of independent sources using a truncated Taylor Series expansion.
- Combine normalized error sources using a root sum of squares (RSS) type norm.





Methodology (cont.)

- ISO 5436-1 Type A1 depth measurement standard used to guide assessment regions.
  - Exclusion zones around high angle features are based on step width.
  - Masked region width is used in erosion measurements.
- Calculation of erosion rate is based on average step height and segment time.
  - Left/right steps may differ if erosion process is asymmetric.
  - Measurements are considered for azimuthal asymmetry.

$$a(t) = \int_{t_0}^{t} E(\tau)d\tau$$

$$E_j = \frac{da(t)}{dt} \approx \frac{\Delta a_j}{\Delta t_j}$$

Sources of Uncertainty

Source	Relative Uncertainty	Parameters of Interest	Parameter Description
Calibration uncertainty	$e_{cal} = \frac{U_{cal}}{\bar{a}}$	U_{cal}	Calibration uncertainty, see table 2.
Component roughness, masked region	$e_{masked} = \frac{t_{99\%,\nu} s_{masked}}{\bar{a}\sqrt{n_{masked}}}$	s_{masked} n_{masked}	Masked standard deviation, Masked measurement count.
Component roughness, exposed region	$e_{exposed} = \frac{t_{99\%,\nu} s_{exposed}}{\bar{a}\sqrt{n_{exposed}}}$	$s_{exposed}$ $n_{exposed}$	Exposed standard deviation, Exposed measurement count.
Component waviness	$e_{wavy} = \frac{U_{wavy}}{\bar{a}}$	U_{wavy}	Deviation of surface from straight line background correction.
Segment time off-point	$e_{time} = \frac{U_{time}}{\bar{a}}$	U_{time}	Operating time spent at off nominal wear point.

Sources of Uncertainty

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Comp… expos…			…n, …nt.
Comp…			…straight …n.
Segme…			

Factor	Factor Range	Factor Description
Step Size	1-15 µm	Physical distance between single measurement locations.
Averaging	1-20 points	Repeated measurement averaging performed at a single location.
Acquisition Rate	200-1000 Hz	Sampling frequency of the collection optics.
Brightness	25-100%	Illumination brightness intensity of the optics.
Focus Height	744-2047 µm	Nominal distance between optics and surface feature.
Off-Nominal Tilt	±5°	Angle between optics and surface feature.

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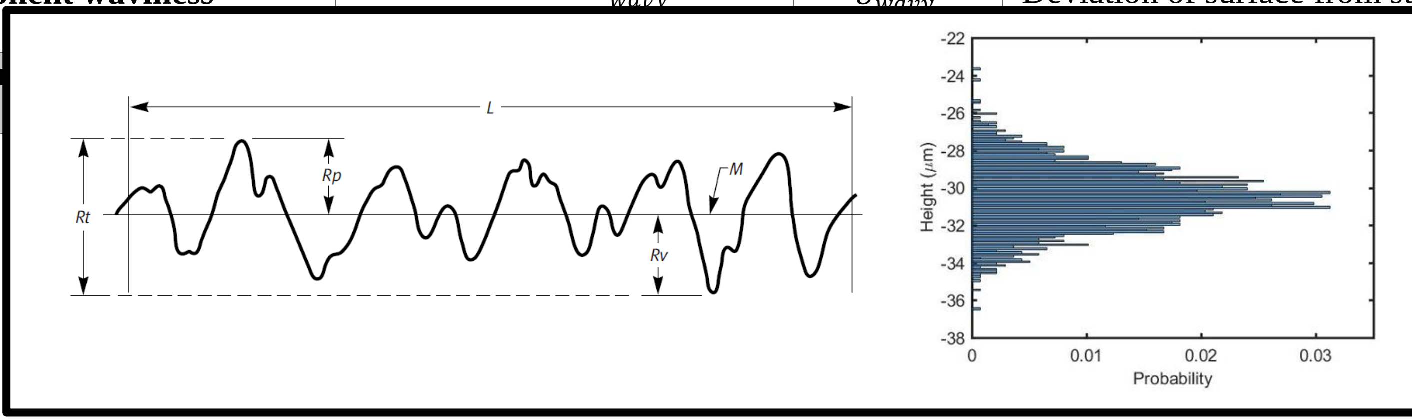
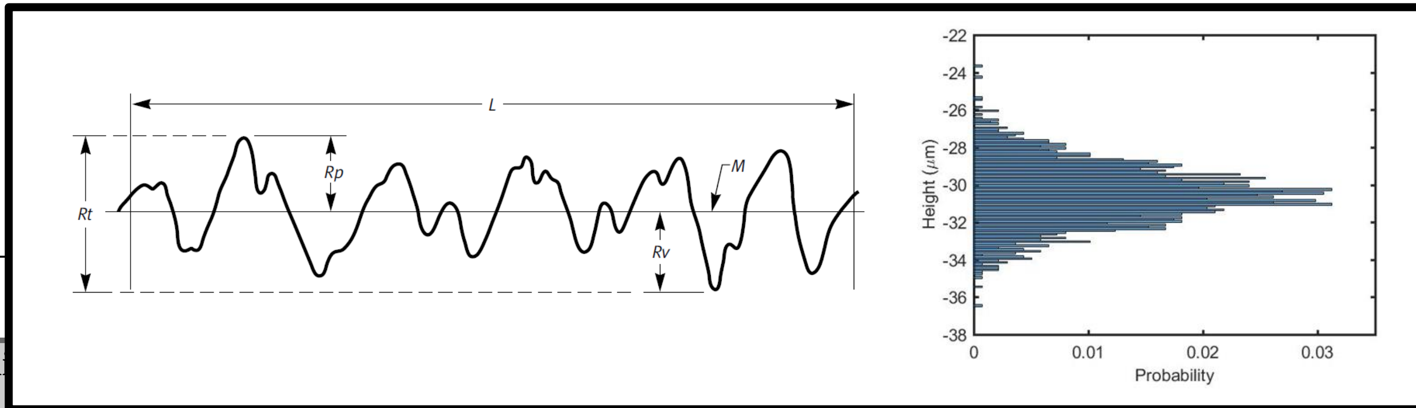
Component waviness	U_{wavy}	U_{wavy}	Deviation of surface from straight
Segmen			



Sources of Uncertainty



			tion
Cal			ee table
Component roughness, masked region	$e_{masked} = \frac{t_{99\%,\nu} s_{masked}}{\bar{a}\sqrt{n_{masked}}}$	s_{masked} n_{masked}	Masked standard deviation, Masked measurement count.
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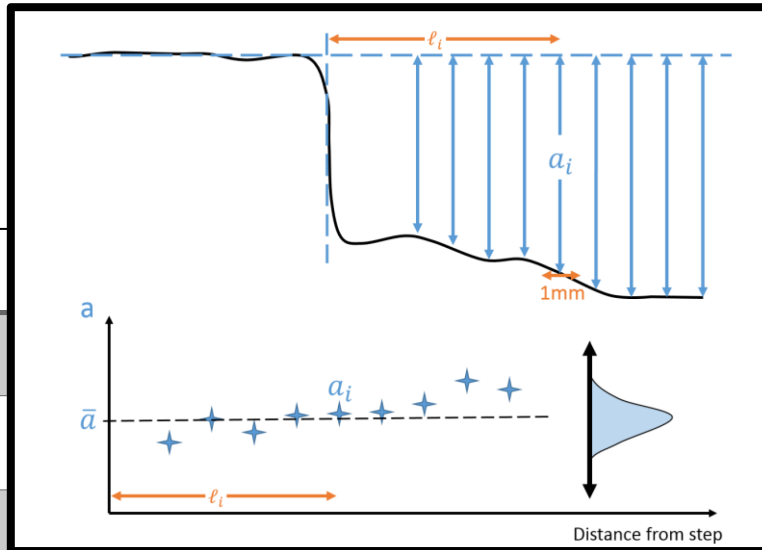
Component waviness	$e_{wavy} = \frac{U_{wavy}}{\bar{a}}$	U_{wavy}	Deviation of surface from straight line background correction.
Segment time off-point	$e_{time} = \frac{U_{time}}{\bar{a}}$	U_{time}	Operating time spent at off nominal wear point.

Sources of Uncertainty



Source			Parameter Description
Calibration uncertainty			alibration uncertainty, see table
Component roughness, masked region			asked standard deviation, asked measurement count.
Component roughness, exposed region	$a\sqrt{n_{exposed}}$	$n_{exposed}$	xposed standard deviation, Exposed measurement count.
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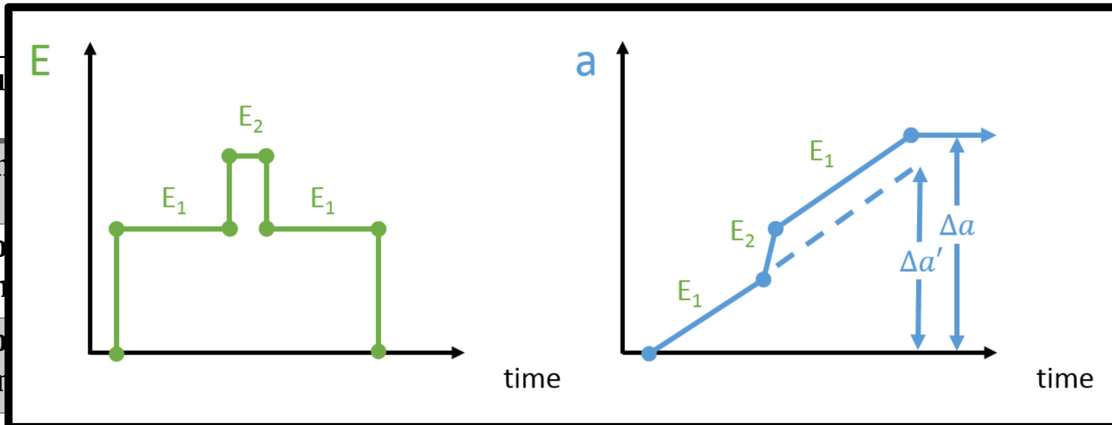

Sou			er Description
Calibration un			ertainty, see table
Component ro masked region			rd deviation, rement count.
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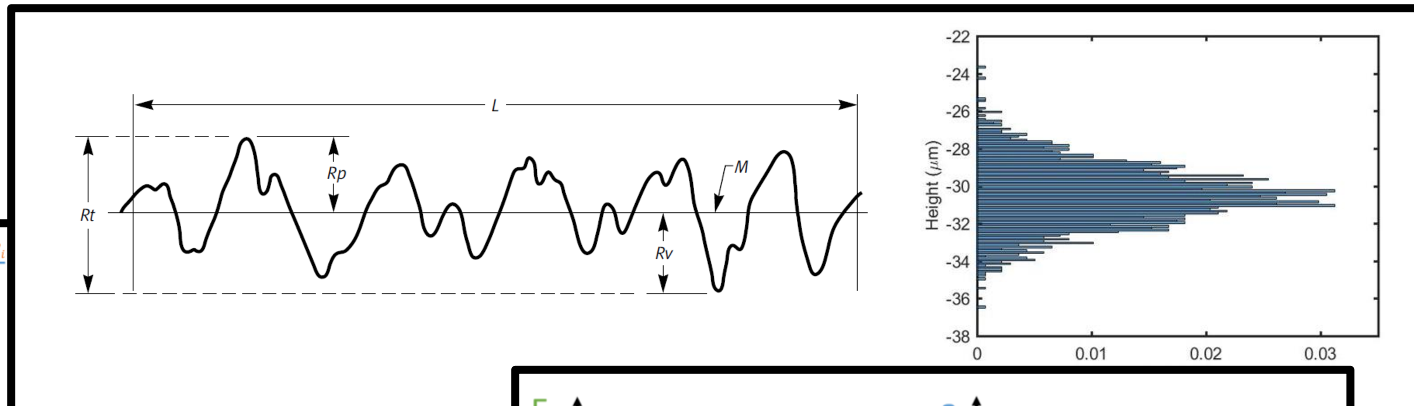
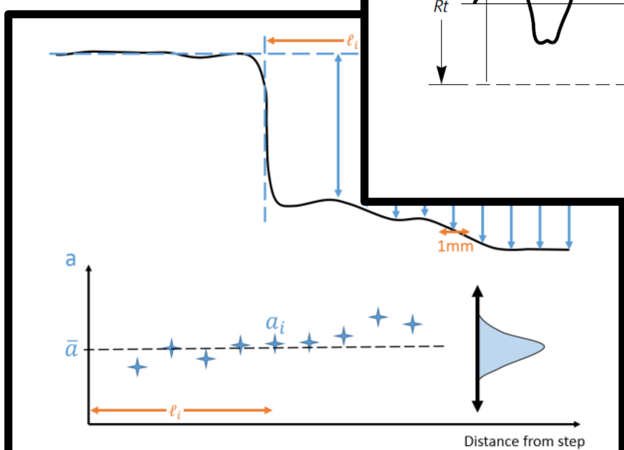
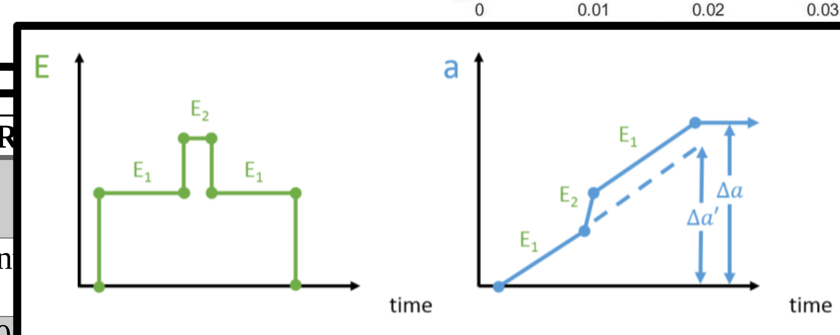
Segment time off-point	$e_{time} = \frac{U_{time}}{\bar{a}}$	U_{time}	Operating time spent at off nominal wear point.

Combination of Sources

$$U_E = \frac{\tilde{a}e_{masked} + \tilde{a}e_{exposed} + \sqrt{(\tilde{a}e_{cal})^2 + (\tilde{a}e_{wavy})^2 + (\tilde{a}e_{time})^2}}{\Delta t}.$$



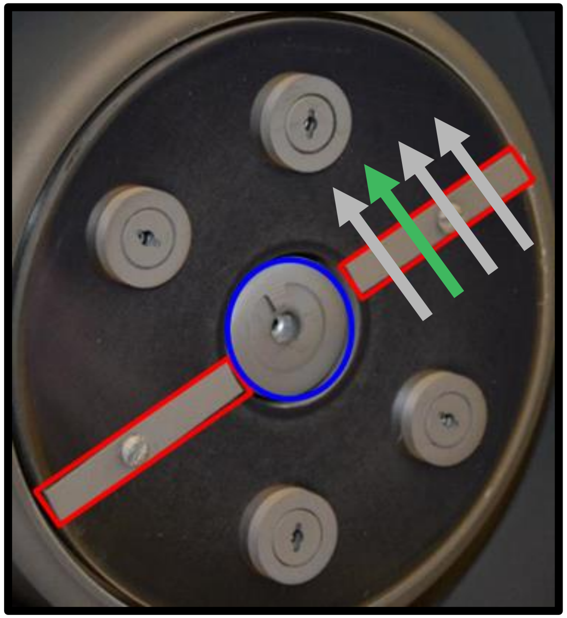


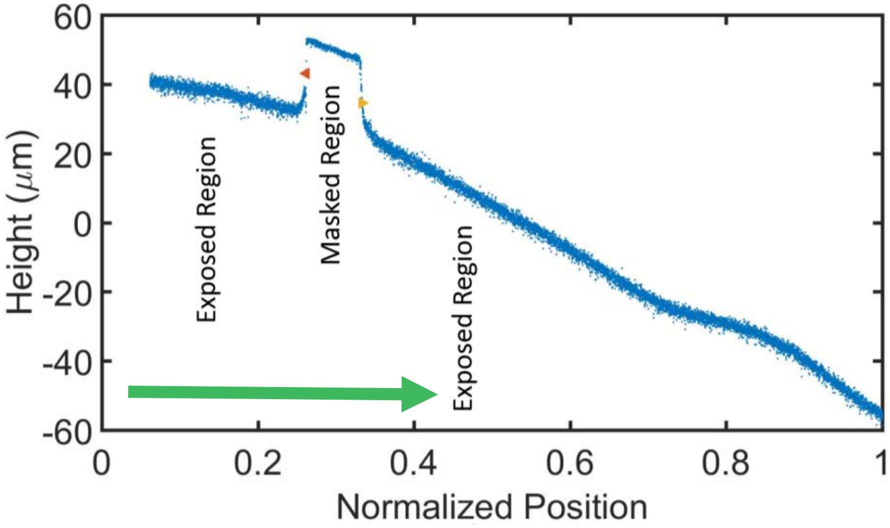


	Factor R	
	1-15 µm	
	1-20 poin	
Acquisition Rate	200-1000	
Brightness	25-100%	Illumination brightness intensity of the optics.
Focus Height	744-2047 µm	Nominal distance between optics and surface feature.
Off-Nominal Tilt	±5°	Angle between optics and surface feature.

Case Study Graphite Pole Cover

- Graphite inner front pole cover eroded for 1015 hours.
- At beginning of segment cover was polished to uniform finish.
- Erosion steps were measured at several radial locations across two masked components.
- One example trace is presented for clarity.





Case Study Graphite Pole Cover

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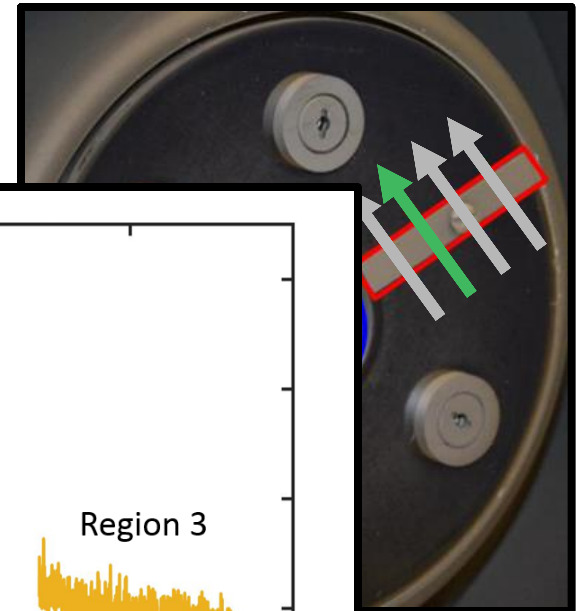
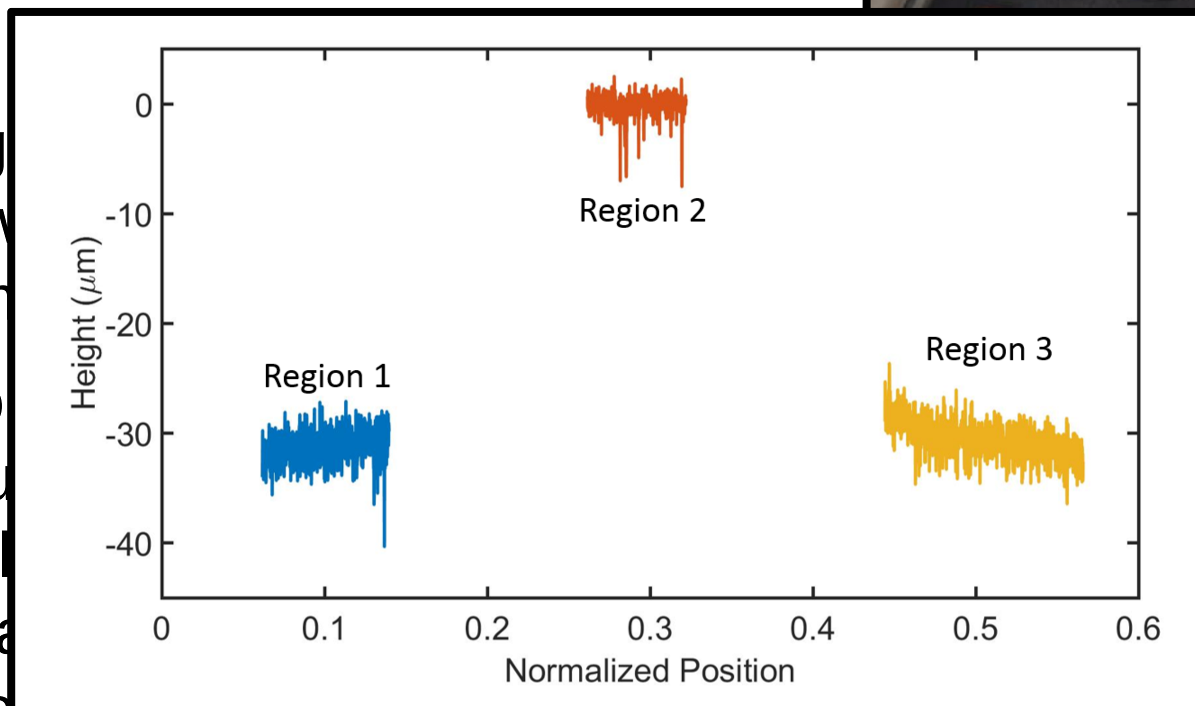
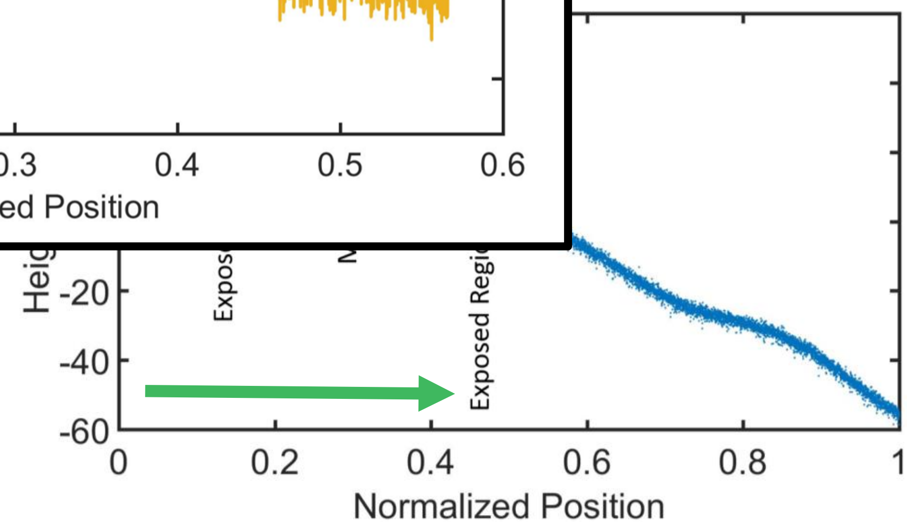




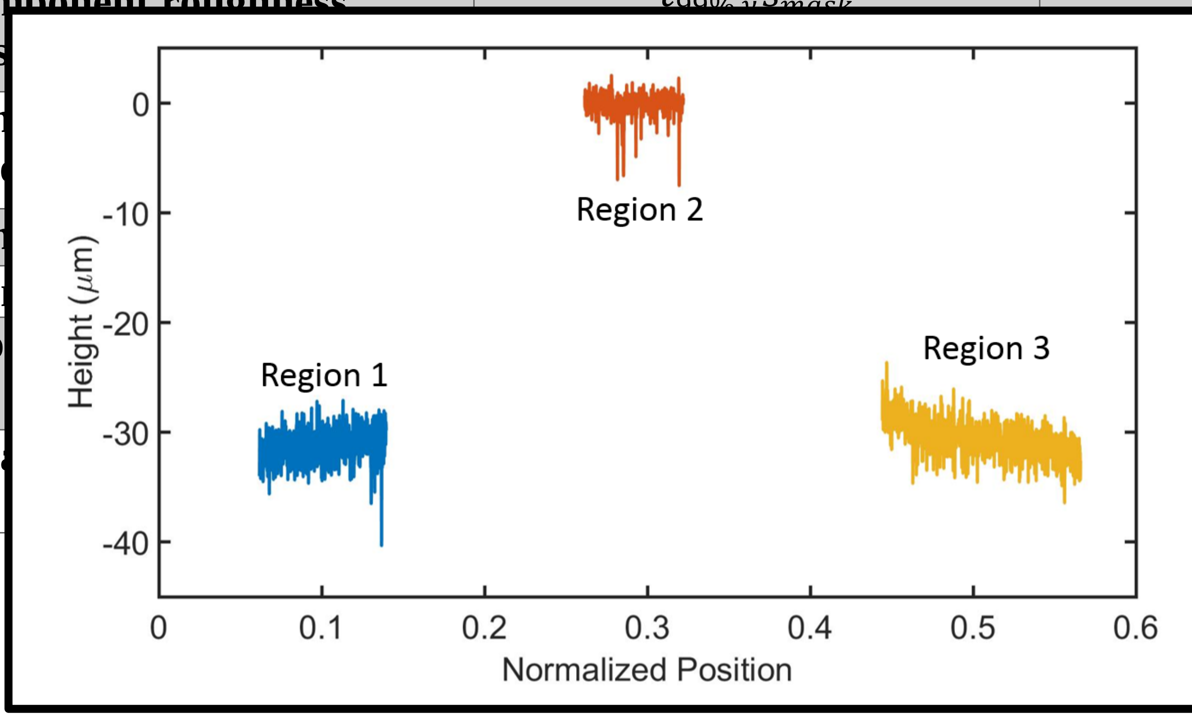


Summary of Assumed Values

Parameter	Term	Value
Average step	$\tilde{a}$	30.82 µm
Calibration uncertainty	U_{cal}	0.54 µm
Component roughness, masked region	$\frac{t_{99\%,v} s_{mask}}{\sqrt{n_{mask}}}$	0.08 µm
Component roughness, exposed region	$\frac{t_{99\%,v} s_{exposed}}{\sqrt{n_{exposed}}}$	0.10 µm
Component waviness	U_{wavy}	2.26 µm
Segment time off-point	U_{time}	0.63 µm
Erosion rate	E	$30.36\ \frac{\mu m}{khr}$
Total rate uncertainty	U_E	$2.54\ \frac{\mu m}{khr}$

Summary of Assumed Values

Parameter	Term	Value
Average step	$\tilde{a}$	30.82 µm
Calibration uncertainty	U_{cal}	0.54 µm
Component roughness mas	$t_{99\%,\nu}s_{mask}$	m
Con exp		m
Con		m
Seg		m
Ero		µm / khr
Tot		m / hr

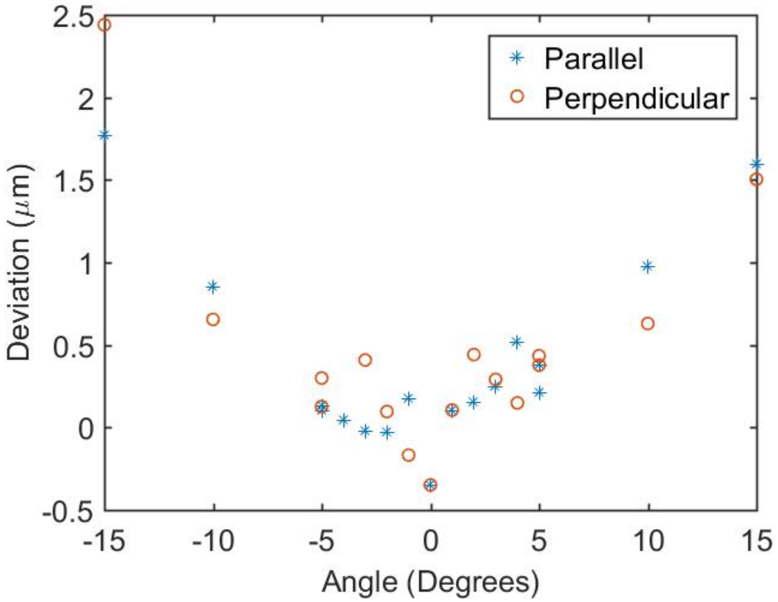


Summary of Assumed Values

Parameter	Term	Value
Average step	$\tilde{a}$	30.82 µm
Calibration uncertainty	U_{cal}	0.54 µm
Component roughness.	$t_{99\%,\nu} S_{mask}$	

Step Size (µm)	Averaging (Count)	Rate (Hz)	Brightness (%)	Tilt (Deg)	Deviation (µm)
1	16	200	100	0	-0.521
5	16	200	100	0	-0.505
10	16	200	100	0	-0.481
15	16	200	100	0	-0.768
1	4	200	100	0	-0.528
1	8	200	100	0	-0.648
1	12	200	100	0	-0.556
1	20	200	100	0	-0.496
1	16	400	100	0	-0.504
1	16	1000	100	0	-0.584
1	16	200	25	0	-0.550
1	16	200	50	0	-0.627
1	16	200	75	0	-0.655
1	16	200	100	-5	-0.127
1	16	200	100	-4	-0.409
1	16	200	100	-3	-0.097
1	16	200	100	-2	0.167
1	16	200	100	-1	0.348
1	16	200	100	1	-0.106
1	16	200	100	2	-0.442
1	16	200	100	3	-0.291
1	16	200	100	4	-0.149
1	16	200	100	5	-0.378

Repeated for:
10µm and 50µm Standards
3mm and 20mm Optics
Final Result is 2σ



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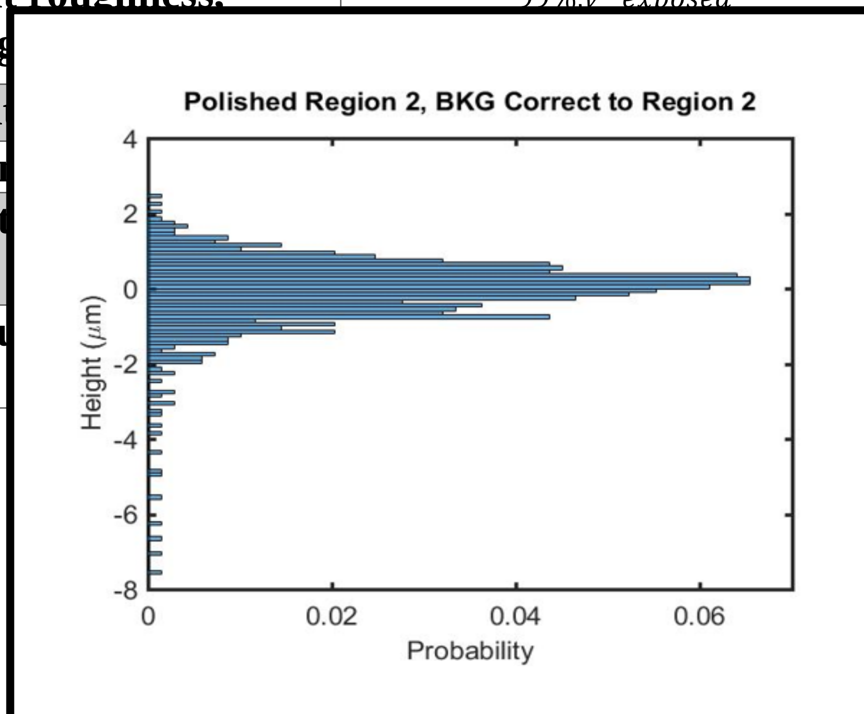
Component roughness, exposed reg	$t_{99\%,\nu} s_{exposed}$	0.10 µm
Component		2.26 µm
Segment ti		0.63 µm
Erosion rat		$30.36 \frac{\mu m}{khr}$
Total rate u		$2.54 \frac{\mu m}{khr}$



Summary of Assumed Values

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Component waviness	U_{wavy}	2.26 µm
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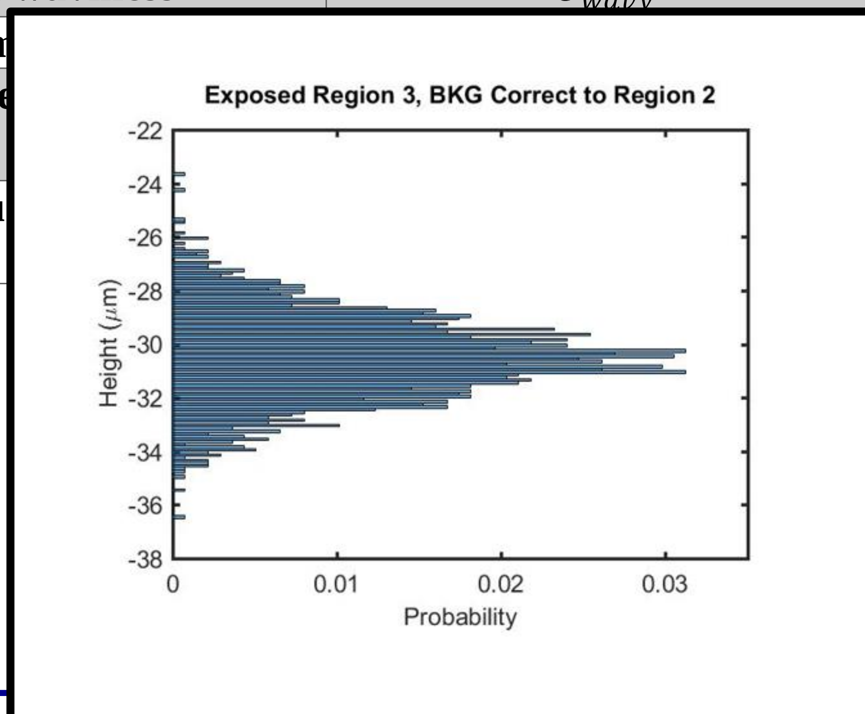
Erosion rate		30.36 $\frac{\mu m}{khr}$
Total rate u		2.54 $\frac{\mu m}{khr}$



Summary of Assumed Values

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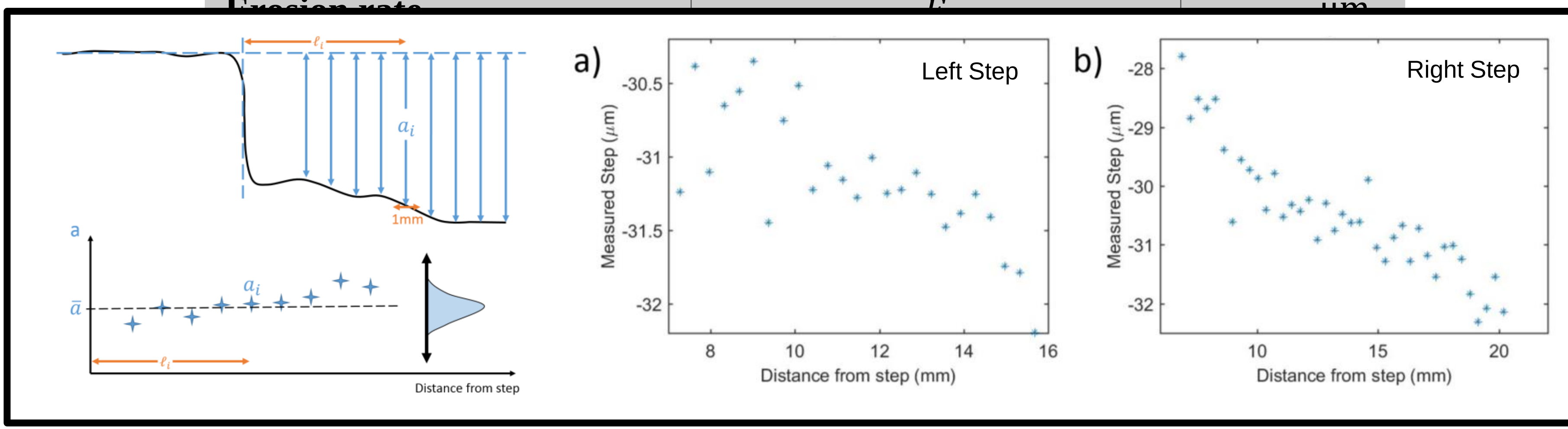
Component roughness, exposed region	$\frac{t_{99\%,\nu} s_{exposed}}{\sqrt{n_{exposed}}}$	0.10 μm
Component waviness	U_{wavy}	2.26 μm
Segment time off-point	U_{time}	0.63 μm
Erosion rate	E	[illegible] μm



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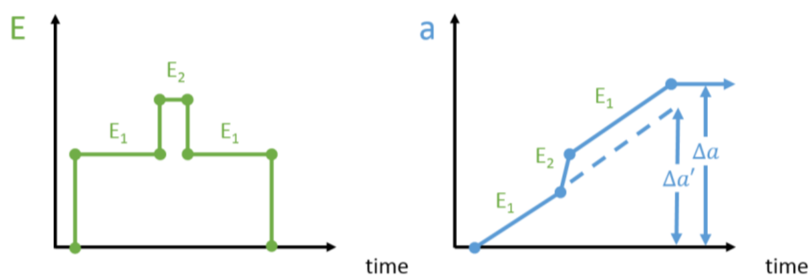
Component waviness	U_{wavy}	2.26 µm
Segment time off-point	U_{time}	0.63 µm
Erosion rate	E	$30.36\ \frac{\mu m}{khr}$



Thruster Condition	Estimated Erosion Rate (µm/khr)	Time (hr)	Accumulated Uncertainty (µm)
1	60	4.3	0.17
2	60	5.3	0.20
3	40	6.1	0.12
4	30	6.1	0.05
5, Nominal	21	1015.0	0.00
6	40	4.6	0.09

Summary of Assumed Values

Parameter	Term	Value
Averag		m
Calibr		m
Compo masked		m
Compo expose		m
Component waviness	U_{wavy}	2.26 µm
Segment time off-point	U_{time}	0.63 µm
Erosion rate	E	$30.36\ \frac{\mu m}{khr}$
Total rate uncertainty	U_E	$2.54\ \frac{\mu m}{khr}$

$$E_j = \frac{da(t)}{dt} \approx \frac{\Delta a_j}{\Delta t_j}$$

$$U_E = \frac{\tilde{a}e_{masked} + \tilde{a}e_{exposed} + \sqrt{(\tilde{a}e_{cal})^2 + \left(\tilde{a}e_{wavy}\right)^2 + (\tilde{a}e_{time})^2}}{\Delta t}$$

Practical Case Study

- 1015 hour segment of the previous case study is long for research.
- A more practical research segment is on the order of 100s of hours.
- Case below demonstrates uncertainty calculated for a 250 hour run.
  - Different operating conditions than the previous case.

Parameter	Term	Value
Average step	$\tilde{a}$	12.61 μm
Calibration uncertainty	U_{cal}	0.54 μm
Component roughness, masked region	$\frac{t_{99\%,\nu} s_{mask}}{\sqrt{n_{mask}}}$	0.12 μm
Component roughness, exposed region	$\frac{t_{99\%,\nu} s_{exposed}}{\sqrt{n_{exposed}}}$	0.15 μm
Component waviness	U_{wavy}	1.73 μm
Component waviness	U_{wavy}	3.34 μm
Segment time off-point	U_{time}	0.63 μm
Erosion rate	E	$50.43\ \frac{\mu m}{khr}$
Total rate uncertainty	U_E	$14.85\ \frac{\mu m}{khr}$

Results Summary

- Many of the sources of uncertainty are independent of segment run time or absolute step height.
- In general larger erosion steps, longer segment operating times, and higher erosion rates are easier to determine with small relative uncertainty.
- 1015 hour case has 30.36 μm/khr ± 2.54 μm/khr
  - Represents 8.4% measurement uncertainty
- 250 hour case has 50.43 μm/khr ± 14.85 μm/khr
  - Represents 29.4% measurement uncertainty
- Uncertainty estimation is intended to be conservative.
  - Target confidence level is 95%, but some sources are not statistically based.
  - Some sources are estimated based on experience.

Alternative Approach

- Many alternative approaches exist:
  - Direct physical measurements, surface layer activation methods, non-contact measurements, destructive examination of components, actual life testing…
  - Many approaches are limited by schedule and funding for research applications.
- Mass loss of components was tracked for the 250 hour case study presented above.
  - Pole cover lost 0.25% of its mass during the erosion segment.
  - Assuming an average step height of 12.5μm, nominal geometry, uniform density, negligible moisture uptake differences…
    - » The profilometry predicted mass loss is 0.31%.
  - Mass loss provides a simple means of assessing erosion, specifically for design decisions.

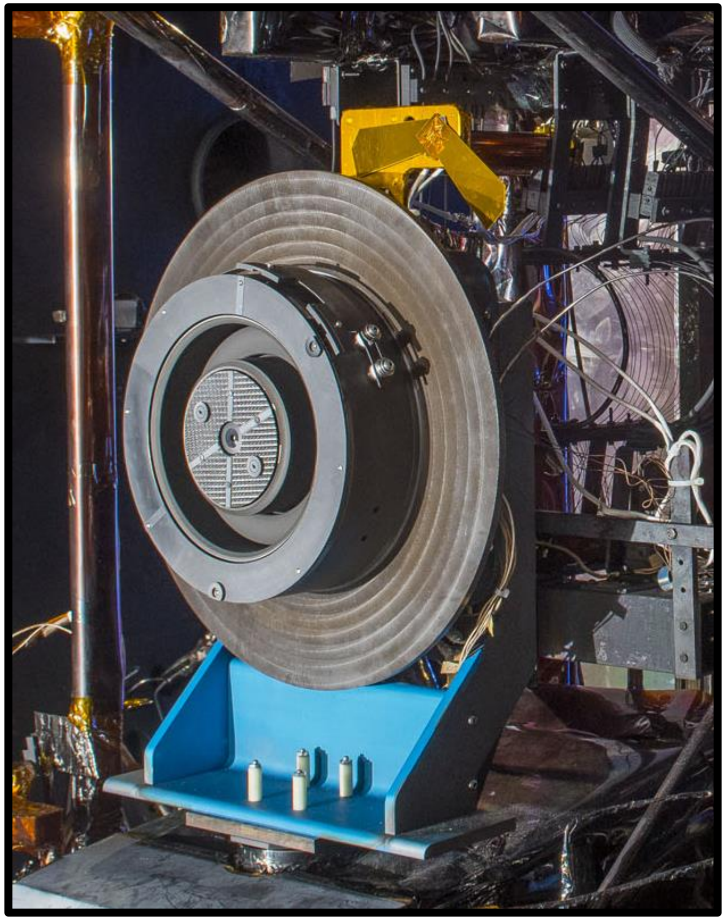
Conclusions

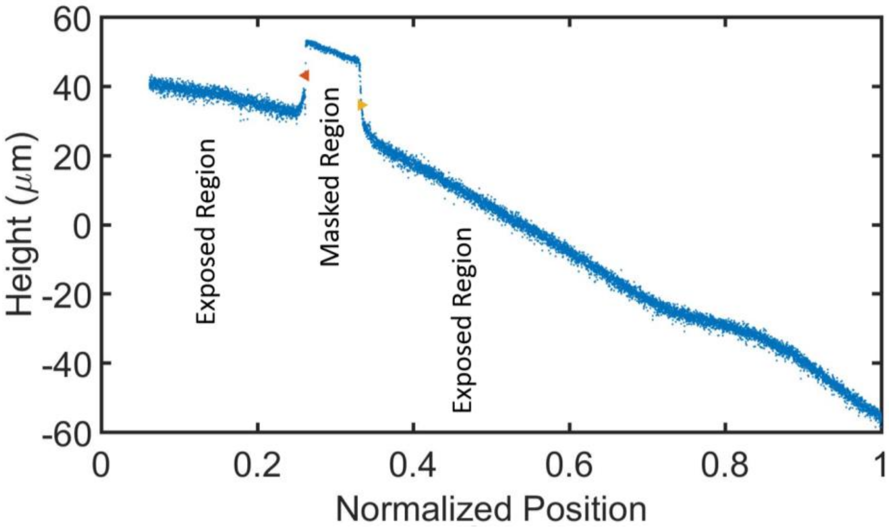
- Uncertainty of non-contact profilometry based erosion measurements has been investigated.
- A number of sources have been identified and quantified.
- Two case studies provide some insight into magnitudes of expected uncertainty.
- Analysis is intended to be conservative and should be used to help guide test planning.
  - Can be used to help determine minimum segment operating times.

Acknowledgements

- Space Technology Mission Directorate in support of the Solar Electric Propulsion Technology Demonstration Mission Project for funding the joint NASA GRC and JPL development of the Advanced Electric Propulsion System.

Questions?




Height (μm)
Normalized Position
Exposed Region
Masked Region
Exposed Region
60
40
20
0
-20
-40
-60
0
0.2
0.4
0.6
0.8
1

NASA